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Key questions about Galactic Center dynamics

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Abstract.   I discuss four key questions about Galactic Center dynamics, their implications for understanding both the environment of the Galactic MBH and galactic nuclei in general, and the progress made in addressing them. The questions are (1) Is the stellar system around the MBH relaxed? (2) Is there a "dark cusp" around the MBH? (3) What is the origin of the stellar disk(s)?, and (4) What is the origin of the S-stars?

1.   Introduction: the dynamical components of the GC

The Galactic Center (GC) is a uniquely accessible laboratory for studying the dynamics of stars and gas in the vicinity of a massive black hole (MBH). Commonly assumed theoretical paradigms for interpreting MBHs—key players in many fields of astrophysics—are strongly challenged by the observations of the GC. In this short review I discuss four key questions about Galactic Center dynamics, their implications, and the progress made in addressing them.

It useful to set the stage by showing the dynamical components of the GC in schematic form (Figure 1.1). The radius of dynamical influence of the MBH extends to ~ 2 pc. Beyond that lies the central star-forming region of the Galaxy on the 100 − 200 pc scale, which is composed of a mixed population of old low-mass and young massive stars (among then presumably many binaries)—evidence of continuous star formation (SF) (Figer et al. 2004). It also includes massive objects such as giant molecular clouds (GMCs) (Oka et al. 2001) and stellar clusters (Figer et al. 1999). Just inside the radius of influence, at a distance of ~ 1.5 pc, lies a ring of less massive molecular clumps (the circum-nuclear disk, CND), which delineates a central region with very little gas. The *observed* stellar population in the central ~ 0.5 pc is composed of red and blue giants, and lower-mass main sequence (MS) stars (the faintest currently observed are B dwarfs). It is assumed that there are many more fainter, yet unobserved lower-mass main sequence stars there, as well as compact remnants: white dwarfs (WD), neutron stars (NS) and stellar mass black holes (BHs). Some over-densities in the stellar distribution in the inner parsec have been interpreted as the dissolving cores of inspiralling clusters held together by an intermediate mass BH (IMBH) (e.g. Maillard et al. 2004). While the red giants and lower-mass B-dwarfs are isotropically distributed, the $O(100)$ blue giants are concentrated in one (or perhaps two) coherently-rotating warped disks, which extend inward to a sharp inner cut-off at ~ 0.04 pc (~ 1"). The inner arcsecond
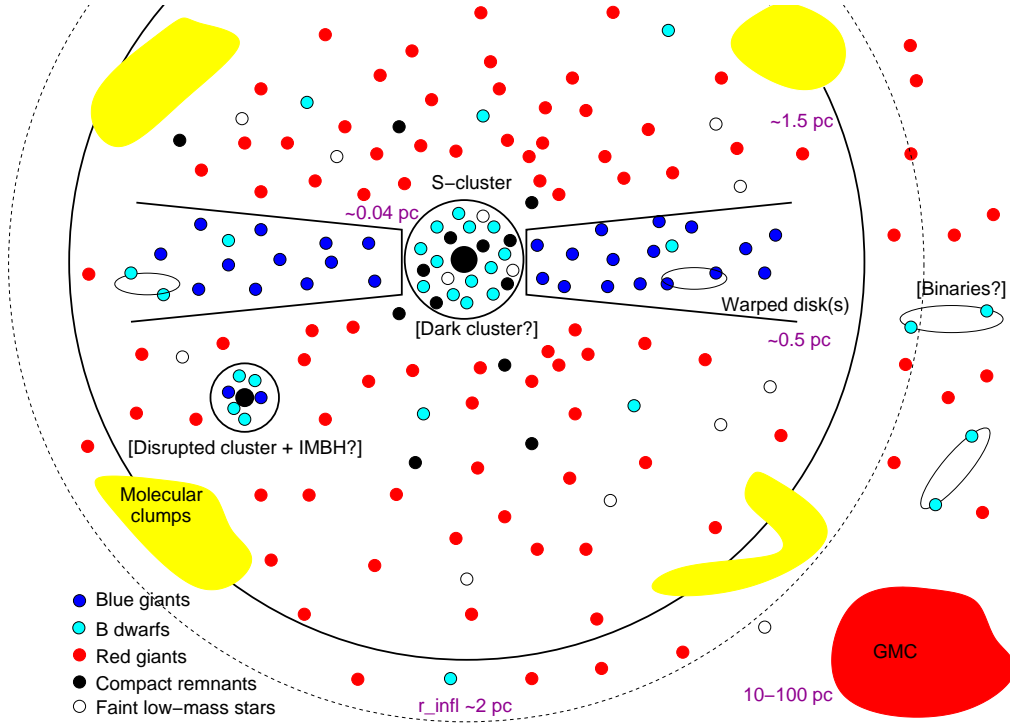
Figure 1.1.   A schematic depiction, not to scale, of the various dynamical components that are observed in the GC around SgrA⋆, or are hypothesized to exist there (these are marked by [...], see section 1).

harbors a spectroscopically and dynamically distinct population of ∼ 40 B-dwarfs on isotropic orbits (the S-cluster).

2.   Is there a relaxed stellar cusp around the MBH?

The most basic, and arguably the most important question about the dynamical state of the GC, is whether it is relaxed or not. An unrelaxed system reflects its particular formation history, which likely varies substantially from galaxy to galaxy. In contrast, the properties of a relaxed system can be understood and modeled from first principles, independently of initial conditions. Lessons learned from a relaxed GC can then be extrapolated to other relaxed galaxies. For example, the hypothesis that such an extrapolation is valid is crucial for understanding the dynamics of extra-galactic gravitational wave (GW) sources and predicting their rates, since the low-mass MBH in the GC is the archetype of extra-galactic targets for the planned space-borne GW observatory LISA (NASA/ESA 2010).

2.1.   Theoretical expectations

The Galactic Center, like other galactic nuclei with low-mass MBHs, is expected to be dynamically relaxed. This follows from the observed correlation between the MBH mass $M_\bullet$ and the typical velocity dispersion of the spheroid of the host galaxy, $M_\bullet \propto \sigma^\beta$

with $4 \lesssim \beta \lesssim 5$ (the $M_\bullet / \sigma$ relation, Ferrarese & Merritt 2000; Gebhardt et al. 2000). To see this, assume for simplicity $\beta = 4$ (a higher value only reinforces this conclusion). The MBH radius of influence $r_h \sim GM_\bullet / \sigma^2 \propto M_\bullet^{1/2}$ encompasses a stellar mass of order $M_\bullet$, so that the number of stars enclosed there is $N_h \sim M_\bullet / M_\star$, where $M_\star$ is the typical stellar mass, and the mean stellar density is $\bar{n}_h \sim N_h / r_h^3 \propto M_\bullet^{-1/2}$. The simple "$nv\Sigma$" estimate of the rate of gravitational encounters then implies that the 2-body relaxation rate is $T_R^{-1}(r_h) \sim \bar{n}_h \sigma (GM_\star / \sigma^2)^2 \propto M_\bullet^{-5/4}$ (note also for future reference that $T_R^{-1} \propto M_\star^2 N_\star$). More rigorous estimates yield for the Galactic MBH ($M_\bullet \simeq 4 \times 10^6 \, M_\odot$, Eisenhauer et al. 2005; Ghez et al. 2005), $T_R \sim$ few Gyr $< t_H$ (the Hubble time) and $\bar{n}_h \sim O(10^5 \, \text{pc}^{-3})$. As argued below, the density in a relaxed stellar cusp near a MBH is orders of magnitude higher still. Since $T_R \propto M_\bullet^{-5/4}$, MBHs with $M_\bullet \lesssim 10^7 \, M_\odot$ are expected to lie in relaxed high density cusps.

By a coincidence of technology, this also happens to be the MBH mass range that LISA is sensitive to. This is why GC dynamics are so relevant for extra-galactic GW sources, in spite of the fact that the chances of detecting GW emission from the GC itself are small (Freitag 2003).

Relaxed stellar systems around MBHs are expected to settle into a centrally concentrated, (formally) diverging density distribution—a cusp. This can easily be seen in the case of a single mass population, which relaxes to an $r^{-\alpha}$ cusp with $\alpha = 7/4$ (Bahcall & Wolf 1976), since the gravitational orbital energy gained by the system when stars are destroyed near the MBH is conserved as it is shared and carried outward by the remaining stars at a rate $\dot{E}(r) \sim E(r) N(< r) / T_R \propto r^{-1} r^{3-\alpha} / r^{\alpha - 3/2} = r^{7/2 - 2\alpha} =$ const (Binney & Tremaine 1987). When the system includes a spectrum of masses, $M_L \leq M_\star \leq M_H$, the approach toward equipartition by 2-body interactions decreases the specific kinetic energy of the high-mass stars, while that of the low-mass stars increases. As a result, the high-mass stars sink and concentrate in the center on the faster dynamical friction timescale $T_{\text{df}} \sim T_R \langle M_\star \rangle / M_H$, while the low-mass stars float out (Spitzer 1987). The lifespans of the hot massive stars in the GC are much shorter than the dynamical friction and relaxation timescales, and therefore these dynamical processes can significantly affect only longer-lived lower mass, faint stars, and compact remnants. In particular, stellar mass BHs ($M_\star \sim 10 \, M_\odot$), which are substantially more massive than any other long-lived species, are expected to form a dense inner "dark cusp" with a very steep inner concentration ($\alpha > 2$) (Alexander & Hopman 2009).

These general theoretical considerations logically lead to two conclusions: (1) Relaxed systems around MBHs are cusps. (2) Systems without a cusp (e.g. with a flat density core) are not relaxed.

2.2. The observed stellar distribution in the GC

Attempts to characterize the stellar distribution around the Galactic MBH, first by the integrated light and later by star counts, have a long history of conflicting results (see e.g. review by Genzel et al. 1994). Stellar surface number density maps of the entire stellar population above the detection threshold (i.e. including both young and old stars) unambiguously indicate a somewhat shallower cusp than expected, but one still broadly consistent with the predicted relaxed cusp in the GC (e.g. Schödel et al. 2007).

Very recently this picture was overturned with the addition of newly available stellar classifications for the stars around the MBH, using narrow band photometry or spectroscopy (Bartko et al. this volume; Buchholz et al. Buchholz et al. 2009; Do et al.

Do et al. 2009; also in this volume). These observations reveal that the cusp is mostly or solely composed of massive young stars, whereas the old population exhibits a core inside ~ 0.5 pc, or perhaps even a central depletion.

2.3. Interpretation and implications

The observed old stars ($K \lesssim 17$ mag) are all red giants. A key assumption in interpreting their surface density distribution as evidence for the absence of a relaxed cusp is that the giants (typically ~ 0.01 of an old stellar population) faithfully track the distribution of the overall old population.

The observed core in the giant distribution could still be reconciled with a relaxed old cusp if some selective mechanism preferentially destroys giants, or rejuvenates them to appear as hot stars. The latter would also naturally explain why the inner cusp of young stars appears to seamlessly continue the old cusp outside the inner ~ 0.5 pc. Such destruction and rejuvenation models, which were originally studied in some detail as possible explanations for the existence of hot stars in the central parsec (see e.g. review by Alexander 2005), have been since abandoned in favor of *in situ* SF (section 4). It is also unlikely that such processes (tidal heating, Alexander & Morris 2003; envelope stripping by star-giant collisions, Alexander 1999; Bailey & Davies 1999) can be effective outside the central ~ 0.1 pc. An extremely massive cluster of stellar mass BHs born locally from a top-heavy, continuously forming stellar population (section 4) could conceivably destroy the giant progenitors while still on the main sequence throughout the central ~ 0.5 pc (Davies et al., this volume). However, the required mass of this dark cluster exceeds the dynamical limits on the stellar mass around the Galactic MBH, and is inconsistent with the "drain limit" (a conservative upper limit on the steady state number of stellar mass BHs that can survive rapid mutual scattering into the MBH, Alexander & Livio 2004). At this time none of the proposed selective destruction or rejuvenation mechanisms can plausibly reconcile the giant core with an old main-sequence relaxed cusp.

The alternative, that the giants do trace the old population, that there is no cusp, and that the GC is unrelaxed, can perhaps be the result of a major perturbation that ejected the stars from the GC ("cusp scouring") sometime in the past. This would increase the local relaxation time in the center beyond the Hubble time. The GC would then still be away from equilibrium, slowly returning to steady state by 2-body stellar relaxation (Merritt, this volume). Such a destructive event could be a major galactic merger involving the coalescence of the two MBH (Milosavljević et al. 2002). It should be noted however that a major merger is not *required* to explain the growth of the low-mass Galactic MBH (it could grow by the direct accretion of gas and stars, Freitag & Benz 2002), and neither are there any other clear indications of a such a merger in the past apart for the core in the giant distribution.

Several important implications follow from the absence of a cusp, if that is indeed the case. In addition to the fact that the properties of such an unrelaxed core must depend on the details of the core-scouring event, the much lower density of stars around the MBH imply a much lower rate of star-star and star-MBH interactions, and in particular tidal disruption events and GW from extreme mass-ratio inspiral events.

While a slowly evolving, unrelaxed core could explain the observed density distribution, this scenario is not without its problems. The main question is whether the system evolves passively, and on the slow stellar 2-body relaxation time. There are strong reasons to suspect that neither these assumptions is correct.
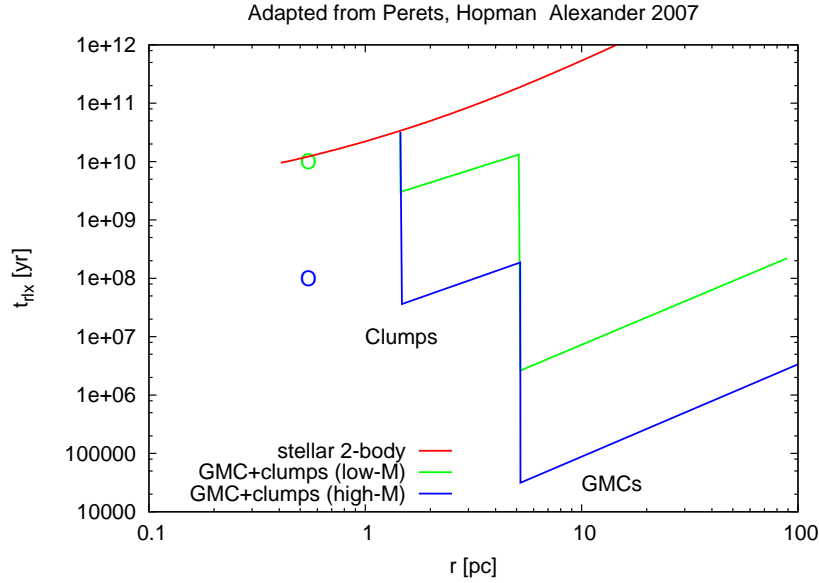
Figure 2.1.   Th,e short relaxation time induced by massive perturbers (mainly GMCs) in the central 100 pc of the GC (Perets et al. 2007). The two bottom sets of curves represent different assumptions about the MP masses. Inside the inner ~ 1.5 pc the local perturbers are stars, but the effects of the gas clumps in the CND extend well within the inner parsec (circles) and can decrease the relaxation time well below the Hubble time.

The latest SF episode in the central ~ 0.5 pc formed $O(100)$ very massive stars that will leave behind stellar BHs (Paumard et al. 2006). There are also indications of a previous SF episode $O(10^8$ yr) ago (Krabbe et al. 1995). On average continuous SF in the GC is the best-fit model to the observed stellar population (Alexander & Sternberg 1999; Baumgardt, this volume). Assuming for simplicity that a 100 stellar BHs of mass $M_\star = 10\,M_\odot$ are formed every 10^8 yr (this is consistent with the $O(10^4)\,M_\odot$ total mass of the progenitor gas disk, Nayakshin et al. 2006), then $N_\star \sim 10^4$ stellar BHs are expected to have accumulated in the central ~ 0.5 pc over a Hubble time. This implies a short two-body relaxation time of only $T_R \sim Q^2 P/\,[2\pi N_\star \log Q] \sim 3 \times 10^9$ yr, where $Q \equiv M_\bullet/M_\star$.

In addition, relaxation in the GC on the $\gtrsim 1$ pc scale is most probably dominated by massive perturbers, primarily giant molecular clouds (GMCs), rather than by stars (Perets et al. 2007). This is because $T_R^{-1} \propto NM^2$ (section 2), and so the $O(100)$ GMCs observed on the l0–100 pc scale with up to ~ $10^7\,M_\odot$, can decrease the relaxation time by many orders of magnitude. Closer to the MBH, on the 1–2 pc scale, the less massive CND gas clumps can decrease the relaxation time well below the Hubble time. The effect of the CND is reduced, but still very substantial, even on the ~ 0.5 pc scale (Figure 2.1). The existence of the S-cluster may be evidence of rapid relaxation by massive perturbers (section 5).

In order for an unrelaxed core to persist in the face of rapid internal (stellar BHs) and external (CND) perturbations, it is necessary to assume that the core was formed recently in cosmological terms, or that both the recent SF activity and the presence of

the CND are atypical. The latter option seems unlikely in view of evidence of continuous SF and GMC creation and breakup in the GC on all scales (Figer et al. 2004; Perets & Alexander 2008). Either of these two explanations implies that we are observing the GC today at a special epoch in its evolution.

3. Is there a dark cusp around the MBH?

A dense, strongly mass-segregated cusp of stellar BHs is expected near the MBH if the GC is relaxed, and even in non-equilibrium core models, the reformation of the BH cusp is rapid, although it does not reach densities as high as predicted for a relaxed system (Merritt, this volume). Such dark nuclear clusters are expected to play a crucial role in the generation of extra-galactic GW signals. However, their existence is yet unconfirmed. Direct detection of the dark cusp in the GC, for example by gravitational lensing (Alexander & Loeb 2001; Chanamé et al. 2001) or by X-ray emission from accretion (Pessah & Melia 2003), is very difficult. Dynamical upper limits on the dark distributed mass within the S-cluster are still at least two orders of magnitude higher than expected from theoretical constraints (Gillessen et al. 2009). At this time, the most promising approach to detect them appears to be through their dynamical interactions with other stars, and in particular by the mechanism of resonant relaxation (RR) (Rauch & Tremaine 1996; Hopman & Alexander 2006).

RR occurs when the gravitational potential has approximate symmetries that restrict orbital evolution (e.g. fixed ellipses in a Keplerian potential; fixed orbital planes in a spherical potential). In such cases the perturbations on a test star are no longer random, but correlated, leading to coherent ($\propto t$) torquing of the orbital angular momentum $\mathbf{J}$ on times shorter than the coherence time t_ω, while the symmetries hold. On longer timescales, coherence is lost as the orbits slowly change by processes such as in-plane precession due to the enclosed mass or due to GR precession, and ultimately, by the RR torques themselves. On these long timescales the orbits evolve in a random walk fashion ($\propto \sqrt{t}$). However, since $\mathbf{J}$ accumulates a very large "mean free path" over the coherence time, the resulting random walk in $\mathbf{J}$ proceeds rapidly on the RR timescale $T_{RR} \ll T_R$.

There are indications that RR can explain some of the dynamical properties of the different populations in the GC (Figure 3.1). The inner limit of the stellar disk coincides with the distance where "Vector RR" (very rapid change in the direction of $\mathbf{J}$ in a spherical potential) randomizes the inclination of disk orbits on a time-scale $T_{RR}^v \sim QP/N_\star^{1/2}$. "Scalar RR" (rapid changes in the magnitude of $\mathbf{J}$ in a Kepler potential, which falls with decreasing distance as $T_{RR}^s \sim QP$ far from the MBH due to the enclosed stellar mass, and then rises again as $T_{RR}^s \sim 6(Q^2/N_\star)(r_g/a)P$ close to the MBH due to GR precession, where $r_g \equiv GM_\bullet/c^2$ and a is the semi-major axis (sma)), could explain the partially randomized eccentricities of the S-stars (Perets et al. 2009). Vector RR may also be responsible for randomizing the orbits of the relaxed giants outside the central 1", which are old in term of their main sequence lifespan, but young compared to the long 2-body relaxation time.

In a multi-mass population, $T_{RR} \propto M_{\text{eff}}^{-1}$, where $M_{\text{eff}} \equiv \left\langle M_\star^2 \right\rangle / \left\langle M_\star \right\rangle$, and so RR is substantially accelerated by mass segregation. It is noteworthy that the random-walk regime of scalar RR depends only on M_{eff}, but *not* on $N_\star$. Scalar RR (rapid eccentricity
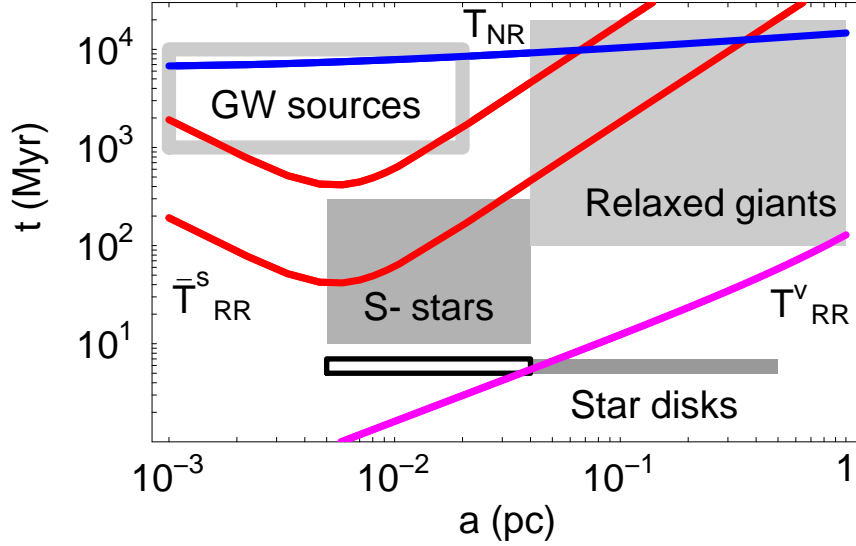
Figure 3.1.   Possible signature of RR in the GC (Hopman & Alexander 2006).
Significant relaxation is expected where the relaxation times are shorter than the
typical ages of the different dynamical components (see text). The two lines for
scalar RR represent different assumptions about M_{eff} (reproduced with permission
from the Astrophysical Journal).

evolution) can therefore probe mass segregation independently of the unknown stellar
distribution around the MBH.

A dark cusp will strongly affect the dynamics of stars on relativistic orbits. These
are of particular interest since they can be used to probe GR in the strong field limit. For
example, the precession of relativistic orbits can be used to test the "No Hair Theorem"
(Will 2008). RR torques by a dark cusp introduce noise to the GR-driven orbital evolu-
tion, which significantly complicates the detection of GR effects (Merritt et al. 2010).
Stars on relativistic orbits can not survive interactions with the MBH and with stellar
BHs for more than $O(10^8 \mathrm{\ yr})$, and therefore they must be continuously replenished, for
example by tidal breakup of incoming binaries (section 5). The dark cusp will influ-
ence the post-capture evolution and survival of such stars. RR and physical collisions,
together with tidal and GW interactions with the MBH, can populate a fraction of the
stars on very relativistic short-period orbits where GR effects are easier to detect, at the
price of destroying a large fraction of them (Figure 3.2).

4.   What is the origin of the stellar disk(s)?

The disk dynamics of the luminous O-stars in the central ~ 0.5 pc of the GC (Levin & Beloborodov
2003; Paumard et al. 2006) set strong constraints on possible formation mechanisms
for the young stars. Two leading possibilities have been considered. The inspiralling
cluster scenario (Gerhard 2001), and *in situ* SF in a massive fragmenting gas disk
(Paczynski 1978; Levin, Nayakshin, this volume).

The infalling cluster scenario is disfavored because even a dense stellar cluster will
disintegrate completely by the MBH tidal field before reaching the central parsec. In
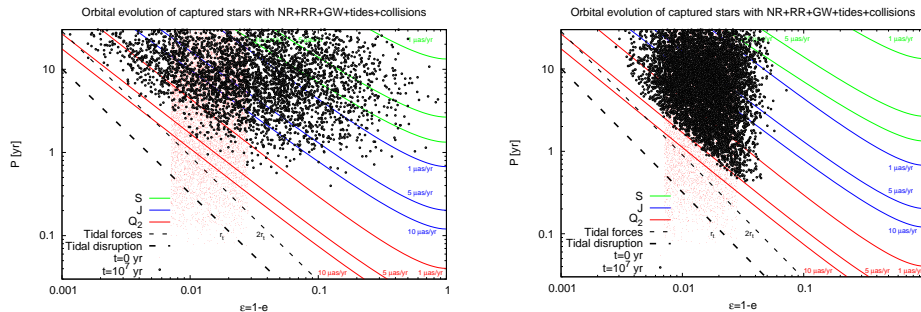
Figure 3.2. The post-capture orbital phase-space evolution of tidally captured stars on relativistic orbits (cf Figure 1 in Will 2008) (Bar-Or, Alexander & Perets, in prep.). Left: The initial distribution (dots) evolves with time by interactions with the dark cusp and the MBH (points). Right: The initial distribution remains relatively unevolved in the absence of a cusp. This leads to a higher survival rate, but also a lower probability of scattering into a short-period relativistic orbit.

order to reach the center, it must be held together by an IMBH (Hansen & Milosavljević 2003), which has to be an implausibly massive one relative to its cluster mass (Gürkan & Rasio 2005). There is to date no compelling evidence for the existence of an IMBH in the GC (Trippe, this volume). Furthermore, a disintegrating cluster is expected to leave a tidal tail of stripped stars over a large range of radii, which are not observed (the distribution of young stars ends quite sharply at ~ 0.5 pc, Paumard et al. 2006).

Observations and modelling currently favor the *in situ* fragmenting gas disk scenario. The mass function of stars born in a disk is expected to be top-heavy because the tidal field of the MBH and the disk temperature imply a higher Jeans mass to begin with, and the massive proto-star further grows by accretion from the disk (e.g. Levin & Beloborodov 2003). There are indeed indications of a top-heavy mass function (Nayakshin & Sunyaev 2005; Bartko et al. 2010; Bartko, Najarro, this volume). The disk displays marked deviations from an ideal flat thin disk, as evidenced by the observed non-circular orbits, warps, wide opening angle, and outlying O-stars (Bartko et al. 2009; Lu et al. 2009). These deviations are interpreted as post-formation evolution (Bartko, Madigan, Perets, this volume). Some of the outlying O-stars may be members of a second, disintegrating counter-rotating disk (Paumard et al. 2006).

The opportunity to observe the products of this new channel of SF, which occurs under conditions that are very different from those of GMC fragmentation elsewhere in the Galaxy, is of obvious significance for understanding SF in general.

5. What is the origin of the S-stars?

The young, seemingly normal main sequence B-stars (Ghez et al. 2003; Eisenhauer et al. 2005) in the inner ~ 1" (~ 0.04 pc) of the Galactic MBH, the so-called "S-cluster", pose one of the most intriguing puzzles of the GC. Simplicity and economy considerations often lead to the natural assumption that the S-stars are associated with the young stars farther out. However, there are significant systematic differences between the S-cluster and the disk stars. Unlike the co-rotating, approximately circular orbits of the disk stars, the S-stars have random orbital orientations with even higher orbital eccentricities than

expected in an isotropic distribution (Gillessen et al. 2009). In addition, the brightest stars in the S-cluster are early B-stars, quite fainter, less massive and longer lived than the very massive O-stars that define the disk.

Generally, any scenario that postulates a disk origin for the S-stars (Milosavljević & Loeb 2004; Löckmann et al. 2009; Madigan et al. 2009; Griv 2010; Madigan, Yelda, this volume), must also be able to explain this "inverse mass segregation" which concentrates the lower mass stars in the center, while leaving the more massive stars farther out. No such compelling scenario has yet been suggested. An alternative explanation that circumvents this problem is that the B-stars are the most massive survivors of a *previous* episode of disk fragmentation, which also produced now-dead O-stars in the S-cluster. However, this then raises the problem why no O-stars from the *present* disk are seen today in the S-stars cluster.

An alternative to *in situ* SF scenarios is to assume that the S-stars migrated to their present position from outside the central parsec (from the "field"), and that they are a distinct population, unrelated to the disk stars. En-mass migration as part of a stellar cluster is disfavored by observations, as discussed above (section 4). A more promising option is individual capture of stars by tidal disruption of incoming binaries (3-body exchanges, Hills 1988; Perets, this volume). This process leaves a distinct imprint on the initial sma and eccentricity distributions of the captured stars. This can be seen by considering for simplicity equal mass binaries of mass $2M_\star$ and sma a_2, which are scattered to the MBH on a parabolic orbit, and are tidally disrupted at a distance $r_t = a_2(M_\bullet/2M_\star)^{1/3}$. The point of disruption then becomes the periapse of the captured orbit with sma a_1 and eccentricity e_1, $r_t = a_1(1 - e_1)$. The orbital energy extracted by the work of the tidal field on the binary, $dE \sim [(GM_\bullet/r_t^3)a_2]r_t \sim GM_\bullet^{1/3}(2M_\star)^{5/3}/a_2$, is carried by the ejected star, so that the captured orbit has energy $-dE$ and $a_1 = -GM_\bullet M_\star/2dE$. Therefore, the typical initial capture sma maps the original binary sma, $\langle a_1 \rangle \sim (M_\bullet/2M_\star)^{2/3}a_2$, and the initial eccentricity is very high and independent of the sma, $\langle e_1 \rangle \sim 1 - (2M_\star/M_\bullet)^{1/3} > 0.95$.

Several lines of evidence support the tidal capture scenario. The luminosity function (LF) of the S-stars is close to the steep (bottom heavy) universal LF that is observed in the field, and is quite unlike the flat (top heavy) LF of the disk stars (Bartko, this volume). This strongly suggests that the S-stars were not formed *in situ*, and are unrelated to the disks. The eccentricity distribution of the S-stars is more eccentric than in an isotropic distribution (Gillessen et al. 2009), although not as biased to high eccentricities as expected for the initial post-capture orbits. This is consistent with efficient post-capture randomization by RR (Figure 5.1) (Perets et al. 2009). The sma distribution the captured stars is harder to predict, since unlike the eccentricity distribution, it depends both on the poorly known sma distribution of the field binaries, and on the details of the scattering process by the perturbers (Perets & Gualandris 2010). The tidal capture mechanism pairs each captured S-star with an ejected hyper velocity star (HVS). The numbers of observed S-stars and HVSs are consistent. The tidal capture mechanism also predicts a temporally continuous distribution of HVSs, which agrees with observations, and a spatially homogeneous distribution, which may not, albeit with still low statistics (Brown et al. 2009) (Brown, Yu, this volume).

Two-body relaxation alone is too slow to deflect massive binaries from the field at a high enough rate to maintain a steady-state population of ~ 40 S-stars. However, such high rates can be driven by the massive perturbers (GMCs) observed on the ~ 5–100 pc scale (Perets et al. 2007). GMCs are known to play an important role in the
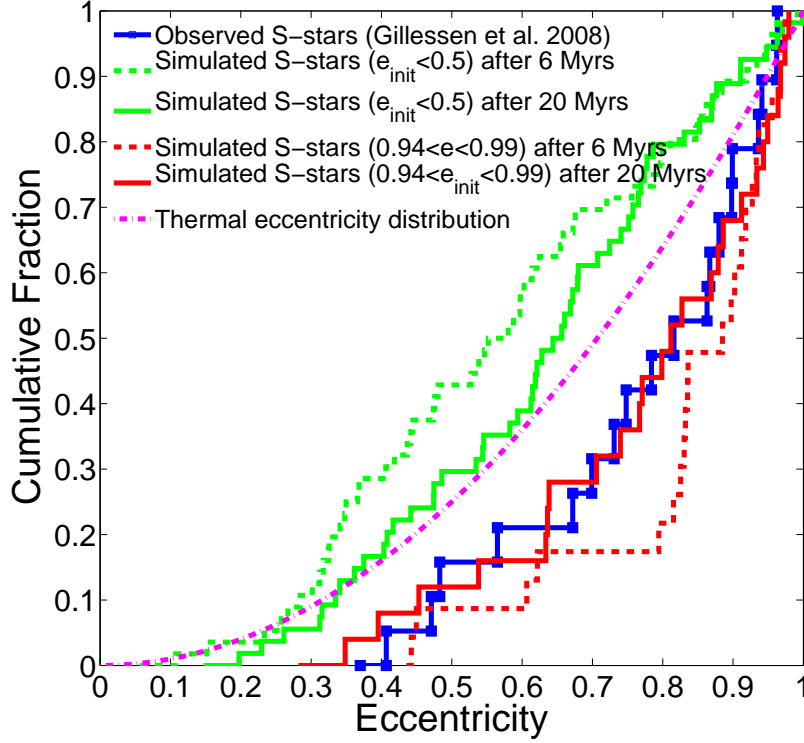
Figure 5.1.   The evolution of S-star eccentricities under different assumed formation scenarios and timescales, as measured in Newtonian *N*-body simulations (Perets et al. 2009). The best fit is obtained for a tidal capture scenario with a high initial eccentricity, which evolves over the typical S-star lifespan of ∼ 20 Myr. Disk origin models with smaller initial eccentricities do not reach the observed eccentricity distribution irrespective of assumed age (whether 6 Myr for the disk, or 20 Myr full lifespan), and instead converge to the isotropic (thermal) distribution (reproduced with permission from the Astrophysical Journal).

dynamics of the Galactic disk on much larger scales (Spitzer & Schwarzschild 1951). Their role in the nuclear dynamics of the Milky Way, suggested by the S-cluster, implies a significance for the nuclear dynamics of gas rich galaxies in general. For example, GMCs can drive binary MBHs in post-merger galaxies to rapid coalescence and the emission of an extremely strong burst of GW radiation (Perets & Alexander 2008).

6.   Conclusions and summary

MBHs play many important roles across all fields of astrophysics. In particular, low-mass MBHs such as the Galactic MBH are the targets of GW searches by LISA. The dynamics of the GC near the MBH are key to testing the validity of commonly held assumptions, frequently used approximations, and theoretical scenarios. Such studies can indicate whether conclusions that apply to the Galactic MBH can be extrapolated to other galaxies, and in general, they provide a realistic assessment of the robustness of

dynamical models of galactic nuclei. This short review focused on four key questions about GC dynamics.

1. **Is the stellar system around the MBH relaxed?** The state of relaxation is directly tied to the shape of the stellar density distribution. A relaxed old population should exhibit a high density cusp. Conversely, a flat core or central depletion implies that the system is unrelaxed and evolving. New observations decisively show that the old red giant population does *not* have a cusp. If the red giants trace the entire population, then the GC is unrelaxed, and its dynamical state reflects some particular initial conditions, which needs not apply to other galaxies.

2. **Is there a "dark cusp" around the MBH?** It is possible that some process selectively destroys red giants, and irrespective of that, fast relaxation mechanisms could accelerate cusp reformation even if it was destroyed by a past events. It is therefore of interest to consider separately the existence of a mass-segregated dark cusp composed of compact remnants, mostly stellar BHs, and faint low-mass stars. Stellar black holes are hard to detect directly, but should have dynamical effects on the orbits of stars. At this time there is no direct evidence for the existence of a dark cusp in the GC.

3. **What is the origin of the stellar disk(s)?** Observations favor *in situ* formation of a top-heavy stellar population in a self-gravitating fragmenting gas disk. The stellar disk (or disks) show evidence of substantial post-formation dynamical evolution.

4. **What is the origin of the S-stars?** Observations favor an origin in the field, rather than *in situ* SF. A promising mechanism is exchange capture of young binaries, which are efficiently deflected from the field by massive perturbers and then undergo post-capture orbital evolution.

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